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by

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EXECUTIVE SUMMARY

Spent carbons from the CIP process were reactivated by applying microwaves. Both 2450 MHz and 915 MHz frequencies were effective in the reactivation of the spent carbon. The best reactivation results in terms of pH, gold adsorption capacity and adsorption rate were obtained by microwaving the spent carbon at 700°C to 750°C for 5 minutes at the peak temperature. Test data confirm that 915 MHz is more effective and in fact at optimum conditions of reactivation more than 95% regeneration of gold absorption capacity took place with 915 MHz whereas only 90% with 2450 MHz in comparison with virgin carbon. Furthermore, only 89% regeneration of gold absorption capacity took place by conventional reactivation of the spent carbon at 750°C for 30 minutes. On the whole microwave reactivated carbon performs better than the thermally reactivated carbon in terms of pH, apparent density, gold absorption capacity and adsorption rate.

Keywords: Microwaves, Carbon Reactivation, Microwave Reactivation, CIP Spent Carbon.

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INTRODUCTION

Microwaves are electromagnetic radiation having frequencies in the range of 300 MHz to 300 GHz and are used extensively in communication applications. Recently, microwaves are finding increasing applications in the operations of heating and drying (1). However, due to communication restrictions only microwaves of 915 MHz and 2450 MHz have been designated for industrial, scientific and medical (ISM) applications (2,3).

Microwave heating is material specific and is caused by molecular dipolar rotation, ohmic heating or interaction of magnetic field components in the magnetic materials (2,3). A large number of minerals including carbon can be heated with microwaves (4-6). As carbon can be heated with microwaves at temperatures above 1000°C (6), it indicated the potential for reactivation of CIP (carbon in pulp) spent carbon with microwaves. Presently, CIP spent carbon is reactivated in rotary kilns heated externally either by electrical power or by natural gas. These reactivation processes seldom ensure uniform heat distribution and the attainment of the final desired temperature in the kiln (7). Figure 1 shows a simplistic flowsheet of the typical CIP operation.

Preliminary test data confirmed that the process of microwave reactivation of the CIP spent carbon had a sound technological potential but its economic viability against the current thermal reactivation process was yet to be studied. The microwave research laboratory of Ontario Hydro in Toronto is adequately equipped for conducting carbon reactivation tests necessary for the economic evaluation of the process. Consequently, a two-part program was initiated with funding under the Canada/Ontario Mineral Development Agreement. This program included contract work by Ontario Hydro's Research Division on the microwave reactivation of CIP carbon and the economics involved, as well as complete characterization and technical evaluation of the reactivated carbon by CANMET. This report

represents CANMET's characterization procedures and evaluation data of the carbons microwave reactivated by Ontario Hydro.

GENERAL PROCEDURE

Several gold mill operations in northern Ontario supplied CIP spent carbons which were all coconut shell charcoal. The as received spent carbon was washed with acidic water (3 kg carbon in 10 L water containing 3% HCl; for 20 min. at 75°C to 80°C). After solid liquid separation carbon was further washed three times with water at ambient temperature. Ontario Hydro performed microwave tests on the washed carbon samples under various conditions with both 915 MHz and 2450 MHz.

Virgin carbon was utilized as received, following a screening to eliminate the fines.

The microwaved carbon samples were evaluated by CANMET in terms of pH, attrition loss (wt%), iodine number (mgI/g C), apparent density (g C/mL), ash content (wt%), surface area (m^2/g C), gold adsorption capacity (K:-Kg Au/t C), and gold adsorption rate (R; mg Au/g C, min^{-1}) by following the standard procedures (8-12).

pH: A properly activated carbon (activated above 500°C) when suspended in water abstracts H^+ and the resulting solution shows alkaline pH.

Ash Content: Non burnable materials (mostly inorganics) left after burning off carbon and other organic components at approximately 650°C. It is an indication of extent of fouling of the carbon.

Apparent Density (AD): Mass of a unit volume of material including both permeable and impermeable voids. This data finds frequent application in the packing of the carbon columns. It is expressed as g C/mL or Kg C/L.

Iodine Number

It is a relative indicator of porosity in an activated carbon. It gives an indication of approximate surface area. It is generally expressed in mgI/g C.

Surface Area

It is the total area per unit mass of a granular carbon which includes all external as well as internal surfaces that are accessible to nitrogen. It is generally expressed as m^2/g C.

Attrition Loss

It is the loss of carbon due to the generation of fines during mixing with the leach pulp and transporting in the CIP circuit. It is measured by screening and weighing of the carbon at the end of each cycle.

Gold Adsorption Capacity (K)

It is the maximum loading of gold on carbon (mg Au/g C or Kg Au/t C) at equilibrium with 1 ppm gold in solution. It is determined by plotting the data in the empirical Freundlich isotherm:

$$\frac{X}{M} = KC^{1/n} \qquad (1)$$

$$\log \; X/M = \log K + 1/n \log C$$

X/M = quantity of Au (mg) adsorption on carbon (g)
K = equilibrium constant
C = equilibrium gold concentration (mg/L)
1/n = slope of the straight line plot

Gold Adsorption Rate (R)

It is a measure of gold absorption against time and determined from the Langmuir reaction rate constant at zero time of the plot of:

$$t/(X/M) = (\frac{1}{M})\, t + \frac{1}{R} \qquad (2)$$

t = time in minutes
X/M = gold loading on carbon (mg Au/g C)
M = reciprocal of the slope
R = reciprocal of the intercept at zero time

Experimental Apparatus

The basic experimental apparatus consists of three main components: a microwave generator (6KW for 2450 MHz and 30 KW for 915 MHz), an applicator where carbon samples were placed for microwaving and a temperature/power monitoring system. Figure 2 shows the general set-up of the test apparatus.

The multimode applicator used for microwaving at 2450 MHz was a stainless steel box having dimensions of 60 cm width x 60 cm height x 75 cm depth. A variable mode stainless steel applicator was used for microwaving with 915 MHz. This applicator was cylindrical in shape with a diameter of 40 cm and height of 80 cm. Both applicators contained several openings and ports for viewing, exhaust, temperature probe and nitrogen gas inlets. A high temperature optical fibre probe connected to a computer data storage and display was used for continuous recording of the temperatures. However, the control of the target temperature during microwaving of the carbon was difficult; very often temperature went above the target temperature by 30°C to 50°C, particularly in the initial tests.

Test Procedure

Carbon samples were placed in a fused quartz crucible containing a known quantity of wet or dry carbon. The crucible was placed in the centre of the applicator floor. The crucible was covered with a microwave transparent but high temperature insulating block with two access holes for temperature and nitrogen gas inlets. In 915 MHz applicator, the temperature probe was inserted through the side of the applicator and the quartz crucible.

After flushing the samples with N_2-gas for 30 seconds microwaving was started. The nitrogen flushing was continued during the entire period of microwaving. All microwaving tests were conducted in batches. Power inputs of 2 KW and 5 KW power of 2450 MHz were applied for microwaving of 100.0 g and 1.5 Kg carbon samples. Whereas 4 KW and 9 KW power inputs of 915 MHz were applied for 100.0 g and 1.5 Kg carbon samples. When the sample was at or near the maximum temperature, the microwave power input was manually adjusted to maintain the temperature at that point for the required length of time. Following microwaving the red hot samples were allowed to cool to

approximately 400°C in a nitrogen atmosphere and then quenched in distilled water.

RESULTS AND DISCUSSION

Optimum temperatures and times for the reactivation of CIP spent carbon were determined for both 2450 MHz and 915 MHz. All the tests were conducted on the scale of 100.0 g of the spent carbon per batch on both wet (50% moisture content) and dry carbons. Because of the complex physicochemical properties of carbon no single parameter can best describe its suitability for the CIP process.

The activated carbons are mainly characterized by pH, apparent density (AD), gold adsorption capacity (K) and gold adsorption rate (R); and occasionally by iodine number and surface area. Nevertheless, physical stability and high gold adsorption capacity are the most desirable properties of the activated carbon for CIP operations. Physically stability is determined by attrition and adsorption capacity by surface area, iodine number and ash content. Properly activated carbon always exhibits a pH above 7. Gold adsorption rate (R) provides data for determining the optimum adsorption time required for the optimum loading of the carbon.

CARBON REACTIVATION AS A FUNCTION OF TEMPERATURE

In order to determine optimum temperature for reactivation, acid washed CIP spent carbon was reactivated at various temperatures with microwaves of 2450 MHz and 915 MHz respectively but for a constant time of 2 minutes of microwaving at the peak temperature. The reactivated carbons were evaluated in terms of physical stability and adsorption properties. Tables 1 and 2 show the test data.

Table 1: Evaluation of the carbons reactivated as a function of temperature; (2 min., 2450 MHz).

Carbon	Activation temp.: °C	pH	AD*: g/mL	Ash Content: Wt%	Attrition Loss: Wt%	Iodine no: mgI/g C	Surface area: m^2/g C	K*: KgAu/t C	R*: m^{-1} Au/g C min^{-1}
Dry Carbon	600°	10.0	0.641	0.470	0.540	364	646	18.44(71%)	0.045
	650°	10.0	0.660	0.480	0.550	328	685	19.12(73%)	0.051
	700°	10.5	0.670	0.510	0.560	370	580	19.43(75%)	0.057
	750°	11.1	0.656	0.510	0.640	356	550	19.22(74%)	0.064
	800°	11.3	0.654	0.460	0.520	350	620	20.14(78%)	0.073
Wet Carbon (50% H_2O)	600°	10.3	0.640	0.410	0.634	368	598	18.07(70%)	0.047
	650°	10.2	0.680	0.500	0.677	361	566	18.65(72%)	0.042
	700°	10.1	0.680	0.440	0.610	318	621	20.40(78%)	0.067
	750°	10.2	0.660	0.420	0.660	319	600	20.60(79%)	0.075
	800°	10.0	0.630	0.410	0.660	345	609	22.67(87%)	0.101
Virgin	-	10.0	0.480	1.260	1.200	400	951	26(100%)	0.33

* AD = apparent density
* K = adsorption capacity
* R = adsorption rate

Percent of K regeneration with respect to virgin carbon in parentheses.

The data in Tables 1 and 2 indicate that the pH of the reactivated carbon samples were in the range of 10.0-11.0 for both dry and wet spent carbon feeds reactivated at temperatures from 600°C to 800°C. The alkaline pH of the reactivated carbon (measured by slurring of the reactivated carbons in distilled water) is an indication of successful reactivation of the spent carbon. Because reactivated carbons have strong tendency to abstract H^+ from water (H_2O) and leave OH^- in the bulk of water. This protonated reactivated carbon functions as a cation exchanger. Generally high temperature reactivation (>500°C) is more favourable for generating carbons with the higher cation exchange properties (8).

Table 2: Evaluation data for the carbon reactivated as a function of temperature; (2 min., 915 MHz).

Carbon	Activation temp.: °C	pH	AD*: g/mL	Ash Content: Wt%	Attrition Loss: Wt%	Iodine no: mgI/g C	Surface area: m^2/g C	K*: KgAu/t C	R*: m^{-1} Au/g C min^{-1}
Dry Carbon	650°	10.1	0.656	0.440	0.510	300	920	21.00(81%)	0.143
	700°	10.2	0.670	0.412	0.500	-	634	22.00(85%)	0.135
	750°	10.2	0.650	0.470	0.450	-	582	22.00(85%)	0.080
	800°	10.8	0.620	0.406	0.410	312	536	23.41(90%)	0.115
Wet Carbon (50% H_2O)	650°	10.2	0.680	0.446	0.520	340	651	20.82(80%)	0.142
	700°	10.8	0.650	0.433	0.500	-	-	23.10(89%)	0.144
	750°	10.8	0.650	0.473	0.500	-	670	23.63(91%)	0.220
	800°	10.8	0.660	0.460	0.460	368	670	23.70(91%)	0.221
Virgin	-	10.0	0.480	1.260	1.200	400	951	26 (100%)	0.33

* AD = apparent density
* K = adsorption capacity
* R = adsorption rate

Percent of K regeneration with respect to virgin carbon in parentheses.

The data in Tables 1 and 2 indicate that temperature has little effect on the ash content of the reactivated carbon. However, ash content of the virgin carbon is high (1.26%) compared with reactivated carbons. The high ash content of the virgin carbon (1.26%) could be due to the presence of inorganic species such as $ZnCl_2$, $MgCl_2$, $CaCl_2$, Na_2CO_3, Fe^{+2}/Fe^{+3} and H_3PO_4 added as the activators to virgin carbon during the activation process (13).

The attrition loss data in Tables 1 and 2 demonstrate that the reactivated carbons are much harder than the virgin carbon. Of course the hardness of the CIP carbon is a desirable property. During the course of reactivation the graphitic structure of the carbon collapses; consequently, the hardness and density of the reactivated carbon increases. However, it is noticed in Tables 1 and 2 that temperature has no obvious effect on apparent density

and attrition losses of the carbon. This phenomenon might be due to inhomogeneous properties of the carbon.

Surface area is an important property of the carbon and arises due to the presence of various types of pores such as macropores (dia. > 50 nm), mesopores (dia. 2-50 nm) and micropores (dia. < 2 nm). Generally micropores represent most of the surface area of the carbon (63%-90%); whereas macropores don't contribute much towards surface area but act as a conduit for the passage of adsorbates into meso and micropores where the majority of adsorption takes place (13).

Surface area data in Tables 1 and 2 demonstrate that the surface area of the carbon has reached a plateau at the reactivation temperatures utilized. The surface area of the virgin carbon (951 m^2/g C) is much higher than that of the reactivated carbons. The maximum surface area of regeneration with respect to virgin carbon were 68% for the carbon reactivated at 650°C with 2450 MHz and 70% for the carbon reactivated at 750°C with 915 MHz.

Iodine number is a measure of adsorption capacity of carbons for iodine and is used as a relative indicator of porosity. Generally, iodine is adsorbed in macropores (dia. 100 nm) (13). Iodine is also adsorbed by unsaturated bondings between carbons. The data in Tables 1 and 2 indicate that activation temperatures have no significant effect on iodine numbers of the carbons; In fact iodine numbers of the acid washed spent carbons from the plants were in the range of 290-372 which are comparable with those of the reactivated carbons (Tables 1 and 2).

Gold adsorption capacity (K) is the single most important property of the CIP carbon. Tables 1 and 2 show K values of the reactivated carbons. It is obvious from those data that K values increase with the rise in reactivation temperatures. For dry carbons the highest adsorption capacities of 20.14 Kg Au/t C and 23.4 Kg Au/t C were obtained by microwaving dry carbons with 2450 MHz and 915 MHz respectively at 800°C which was the highest temperature applied in this series of tests. Similarly, for wet

carbons the highest adsorption capacities of 22.67 Kg Au/t C and 23.70 Kg Au/t C were obtained by microwaving at 800°C with 2450 MHz and 915 MHz, respectively.

It is further evident in these tables that adsorption capacities of the carbon reactivated from wet spent carbon are generally higher than those of the carbons reactivated from the dry spent carbon at a particular temperature. Furthermore, carbon reactivated with 915 MHz provides the higher adsorption capacities. This could be due to the higher penetration power of 915 MHz into the carbon matrix. The data in parentheses in Tables 1 and 2 represent the percent of K regenerated with respect to virgin carbon (K of virgin carbon is taken for 100%). These test data lead to the conclusion that the highest gold adsorption capacity (91%) could be obtained by microwaving the wet spent carbon at 800°C with 915 MHz for 2 minutes

Gold Adsorption Rate (R)

This factor is a measure of gold adsorption in mg Au per gram of carbon in one minute and expressed as [mg Au/g C, min^{-1}]. Generally, the higher R-values are an indication of faster adsorption rate or shorter contact time in a CIP operation. In order to determine R values the adsorption of gold on carbon is first determined from the following equation:

$$carbon\ loading\ (mg\ Au/g\ C) = \frac{X}{M}$$
$$where\ \frac{X}{M} = \frac{(C_o - C_t)}{M}\ V \qquad (3)$$

C_o = initial gold conc. in solution (mg Au/L)
C_t = gold conc. after time t (h)
M = mass of the carbon
V = volume of gold solution (L)

The gold adsorption profile is followed by plotting the percent of gold adsorbed on carbon against adsorption time (hours). Figures 3 and 4 show gold absorption profiles for the carbons reactivated at 700°C and 750°C from wet spent carbon with 2450 MHz; whereas figures 5 and 6 show gold adsorption profiles for carbons reactivated at 700°C and 750°C respectively from wet spent carbon with 915 MHz. Figures 3 and 4 show that 50% of the dissolved gold was adsorbed in less than 2 hours by the carbons reactivated with 2450 MHz; but it took 24 hours for 97% adsorption of gold on the carbon. However, Figures 5 and 6 show it took less than 1 hour to adsorb 50% of the dissolved gold by the carbon reactivated with 915 MHz and only 8 hours to obtain 97% adsorption.

The gold adsorption rate (R) is then calculated as the reciprocal of the intercept at zero time of the plot time divided by gold adsorption (i.e., t/X/m) against contact time (in minutes) of the carbon with a solution of known concentration of gold (Eq. 2). The data in Tables 1 and 2 demonstrate that gold adsorption rate of the carbon increased with the rise in the reactivation temperature. Generally, R values are much higher for the carbons reactivated with 915 MHz than with 2450 MHz.

Carbon Reactivation as a Function of Time

For the determination of optimum reactivation time, samples of acid washed spent carbon were microwaved using 2450 MHz and 915 MHz respectively for various lengths of time but at a constant temperature of 750°C. The reactivated carbon samples were evaluated and Tables 3 and 4 show the data. It is obvious from the tables that the pH's of the reactivated carbons increased steadily with the increase in microwaving time. Even 0.5 minute microwaving with either 2450 MHz or with 915 MHz on dry spent carbon or wet spent carbon yielded reactivated carbons with pH 9.0-9.2. As it appears, from a pH point of view 0.5 minute microwaving of the spent carbon is sufficient to yield reactivated carbon suitable for CIP application.

Table 3: Evaluation of the carbons reactivated as a function of time (750°C; 2450 MHz)

Carbon	Activation time: (min)	pH	AD*: g/mL	Ash Content: Wt%	Attrition Loss: Wt%	Iodine no: mgI/g C	Surface area: m^2/g C	K*: KgAu/t C	R*: mg/Au/g C min^{-1}
Dry Carbon	0.5	9.0	0.646	0.580	0.570	335	540	18.0	0.275
	1.0	10.0	0.640	0.500	0.540	344	600	18.7	0.297
	2.0	10.6	0.656	0.510	0.560	356	580	19.22(74%)	0.064
	5.0	10.8	0.640	0.520	0.490	333	650	19.50(75%)	0.300
	10.0	11.0	0.640	0.480	0.460	330	680	19.00(73%)	0.390
Wet Carbon	0.5	9.2	0.626	0.505	0.600	336	595	21.0	0.685
	1.0	9.0	0.634	0.535	0.630	323	631	19.60	0.350
	2.0	10.0	0.660	0.450	0.660	318	621	20.60(79%)	0.075
	5.0	10.6	0.632	0.470	0.560	343	511	21.50(83%)	0.738
	10.0	11.0	0.630	0.430	0.560	340	620	21.60(83%)	0.547
Virgin	-	10.0	0.480	1.260	1.200	400	951	26 (100%)	0.33

* AD = Apparent density
* K = adsorption capacity
* R = Adsorption rate

Evidently, apparent densities (AD) of the carbons are not affected by the reactivation time. However, reactivation time has some effect in the ash contents of the reactivated carbon; in fact the ash content of the carbon is significantly decreased with the increase in microwaving times at 2450 MHz (Table 3). The data in these tables further indicate that attrition loss or hardness of the reactivated carbon generally increased with the increase in microwaving time.

Iodine number as mentioned before is a measure of macropores in the carbon. Evidently iodine number of the carbons are essentially independent of reactivation time and temperature. Most probably macropore regeneration takes place during acid washing of the spent carbon. In fact iodine numbers of the acid washed spent carbons were found to be in the range of 290-372

Table 4: Evaluation of the carbon reactivated as a function of time (750°C, 915 MHz)

Carbon	Activation time: (min)	pH	AD*: g/mL	Ash Content: Wt%	Attrition Loss: Wt%	Iodine no: mgI/g C	Surface area: m^2/g C	K*: KgAu/t C	R*: mg/Au/g C min^{-1}
Dry Carbon	0.5	9.2	0.651	0.410	0.50	282	610	22.20(85%)	0.191
	1.0	9.8	0.633	0.400	0.59	-	-	23.00(88%)	0.244
	2.0	10.5	0.652	0.420	0.58	312	670	22.80(88%)	0.200
	5.0	10.8	0.642	0.440	0.56	-	630	24.40(88%)	0.180
	10.0	11.2	0.651	0.420	0.55	289	641	24.73(95%)	0.220
Wet Carbon	0.5	9.0	0.640	0.440	0.56	287	603	22.55	0.101
	1.0	10.0	0.650	0.410	0.55	-	575	22.30	0.126
	2.0	10.5	0.660	0.480	0.52	310	600	24.80(95.5%)	0.204
	5.0	11.0	0.670	0.490	0.50	-	670	24.85(95.5%)	0.115
	10.0	11.1	0.650	0.410	0.53	295	650	24.75(95.0%)	0.114
Virgin	-	10.0	0.480	1.260	1.200	400	951	26 (100%)	0.33

* AD = apparent density
* K = adsorption capacity
* R = adsorption rate

which were comparable with those of the reactivated carbons (Tables 3 and 4).

Micropores are the major contributor (63%-90%) to surface area of the carbon (13). During heat treatment (thermal or microwave) micropores are cleaned and more micropores are generated. It is evident in Tables 3 and 4 that there is a general trend of an increase in surface area of the carbon with an increase in microwaving time regardless of microwave frequencies.

Gold adsorption capacities (K) of the reactivated carbons indicate an overall increase with an increase in microwaving time with both 2450 MHz and 915 MHz (Tables 3 and 4). Furthermore, microwaving of the spent carbon with 915 MHz yielded reactivated carbon with higher K values than the carbons reactivated with

2450 MHz. This phenomenon is due to higher penetration power of 915 MHz into the carbon matrix. More than 95% regeneration of K values with respect to virgin carbon were obtained by microwaving wet spent carbon for only two (2) minutes with 915 MHz (data in the parentheses in Table 4). On the basis of these test data optimum microwaving time with 915 MHz could be 2-5 minutes for the wet spent carbon and 5-10 minutes for the dry spent carbon.

Adsorption rate data in Tables 3 and 4 show that, in general, gold adsorption rate is much faster with the carbons reactivated with 2450 MHz than with the carbons reactivated with 915 MHz. In fact 50% of the dissolved gold was adsorbed within 35 minutes by the carbons reactivated with 2450 MHz but 45-50 minutes for the carbon reactivated with 915 MHz. Figures 7,8,9 and 10 show the plots of percents of gold adsorption against contact time.

On the basis of the test data and difficulty in the precise control of the peak temperature the most suitable optimum temperature and time for microwaving of the CIP spent carbon would be 750°C and 5 minutes with either 2450 MHz or 915 MHz. Subsequently several reactivation tests were conducted at these conditions in the scale of 2.0 Kg acid washed spent carbon per batch. Table 5 shows the test data.

The test data in Table 5 further demonstrate that carbon regenerated from wet spent carbon show higher gold adsorption capacities than from the dry spent carbon. These test data also confirmed that 915 MHz is more efficient than 2450 MHz in the reactivation of the spent carbon. In fact the highest gold adsorption capacity (94%) was obtained by reactivating the wet spent carbon with 915 MHz.

Conventionally, CIP spent carbon is regenerated by heating in a rotary kiln at 650°C to 800°C for 25-35 minutes. The kilns are generally heated externally by electrical power or natural gas burners. For direct comparison of the thermally reactivated carbon with the microwave reactivated carbon several thermal

Table 5: Evaluation of reactivated carbons at optimum conditions: 750°C, 5 min.; 2 Kg C/batch.

Microwaves MHz	Carbon	AD* g/mL	pH	Attrition loss: Wt%	Surface area: m^2/g C	Iodine no.: mg/l/g C	K*: kg Au/t/ C	R*: mg/Au/g/ C min^{-1}
2450	Dry	0.662	10.2	0.370	560	386	21.0 (81%)	0.248
	Wet: (50% H_2O)	0.653	10.4	0.560	511	397	23.3 (90%)	0.353
915	Dry	0.670	10.0	0.432	620	352	23.4 (90%)	0.201
	Wet: (50% H_2O)	0.670	10.3	0.510	670	372	24.4 (94%)	0.182

* AD = apparent density

* K = adsorption capacity

* R = adsorption rate

Percents of K regeneration with respect to virgin carbon are in parentheses.

reactivation tests were conducted on the acid washed spent carbon at 750°C for 0.5, 1, 5, 10, and 30 minutes in nitrogen gas atmosphere in a muffle furnace. Table 6 shows the test results.

The data in Table 6 demonstrate that pH's of all the thermally reactivated carbons were in alkaline region and increased with the increase in reactivation time.

The highest pH 11.0 was obtained after 30 minutes of heating; whereas the same pH could be obtained only after 10 minutes of microwaving with 2450 MHz and after 5 minutes with 915 MHz. Apparent densities of the thermally reactivated carbons are higher than those of the microwaved carbon (Tables 3 and 4).

Gold adsorption capacities (K) of the thermally reactivated carbons increased with the increase in time, and the highest gold adsorption capacity (23.25 Kg Au/t C) was obtained after 30 minutes of heating. This highest adsorption capacity represents only 89.4% recovery compared with the virgin carbon (Table 1). However, > 95% recovery of gold adsorption capacity became

Table 6: Evaluation of thermally reactivated carbon (750°C, N_2-atmosphere, acid washed carbon)

Activation time: (min)	pH	K*: kg Au/t C	R*: mg Au/g C min^{-1}	AD*: g/mL
-	-	16.09	0.024	0.704
0.5	9.5	21.90 (84%)	0.054	0.703
1.0	9.9	21.62 (83%)	0.057	0.710
5.0	10.0	22.60 (87%)	0.053	0.717
10.0	10.5	22.80 (88%)	0.050	0.723
30.0	11.0	23.25 (89.4%)	0.062	0.710

* AD = apparent density
* R = adsorption rate
* K = adsorption capacity

Data in parentheses - percents of K regeneration with respect to virgin carbon

possible only after 2 minutes of microwaving (Table 4). These test data further indicated that 87%-88% recovery of gold adsorption capacity of the carbon could be possible by heating the spent carbon for only 5 or 10 minutes at 750°C.

CONCLUSIONS

1. Microwaves of 2450 MHz and 915 MHz can be applied in the regeneration of CIP spent carbon.

2. In terms of pH, apparent density and adsorption capacity microwave reactivated carbon performs better than the thermally reactivated carbon.

3. In comparison with the virgin carbon >95% regeneration of gold adsorption capacity was obtained by microwaving of the spent carbon with 915 MHz at 750°C for only 5 minutes; whereas only 89% of capacity regeneration by conventional heating for 30 minutes.

4. 915 MHz is more efficient than 2450 MHz in the reactivation of the CIP spent carbon.

5. The regeneration of CIP spent carbon with microwaves (2450 MHz or 915 MHz) is a technically feasible process.

6. Presently, a reactor needs to be developed for continuous reactivation of the spent carbon preferably for pilot-scale operation.

7. Further data (capital and operating) for the process of microwave reactivation of the CIP spent carbon are needed for assessment of its industrial application.

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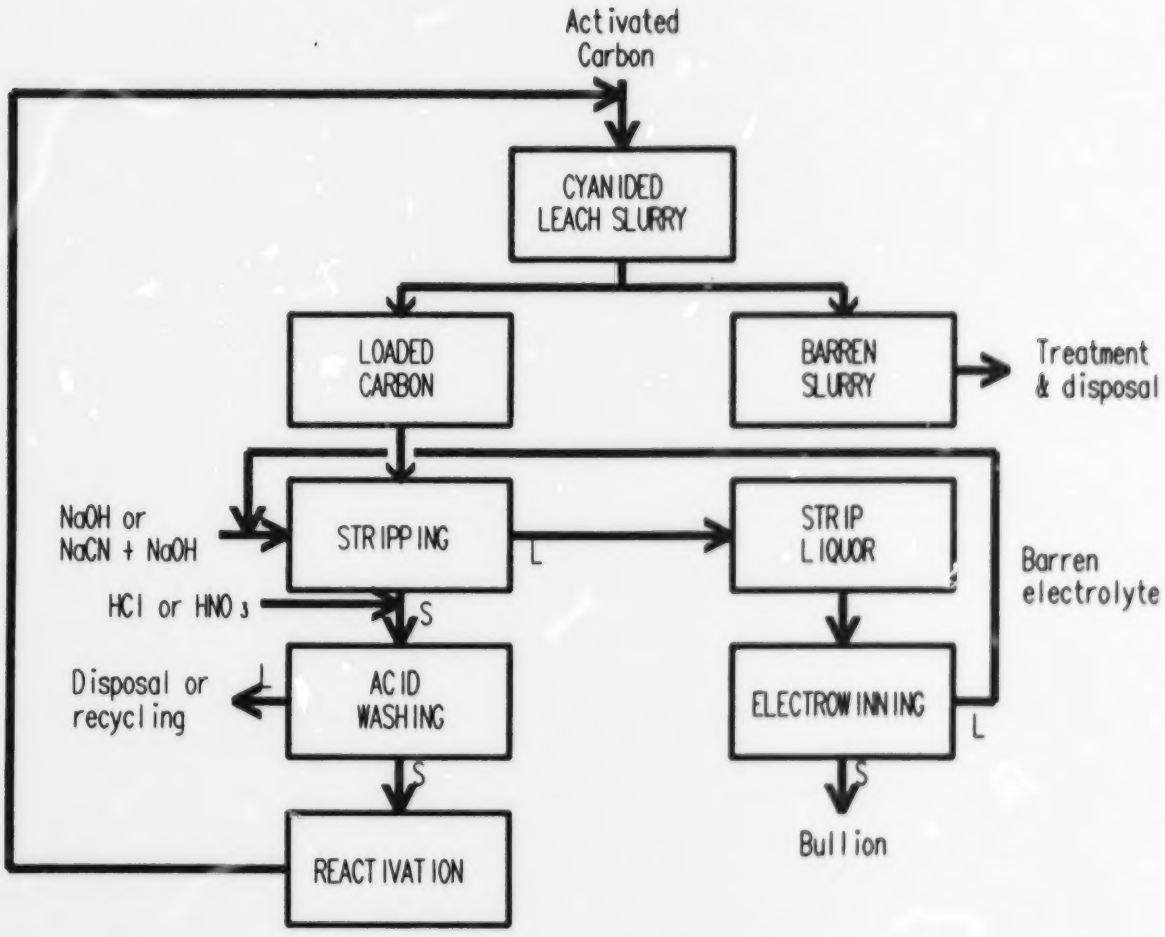

Figure 1. TYPICAL FLOWSHEET OF THE CIP OPERATION

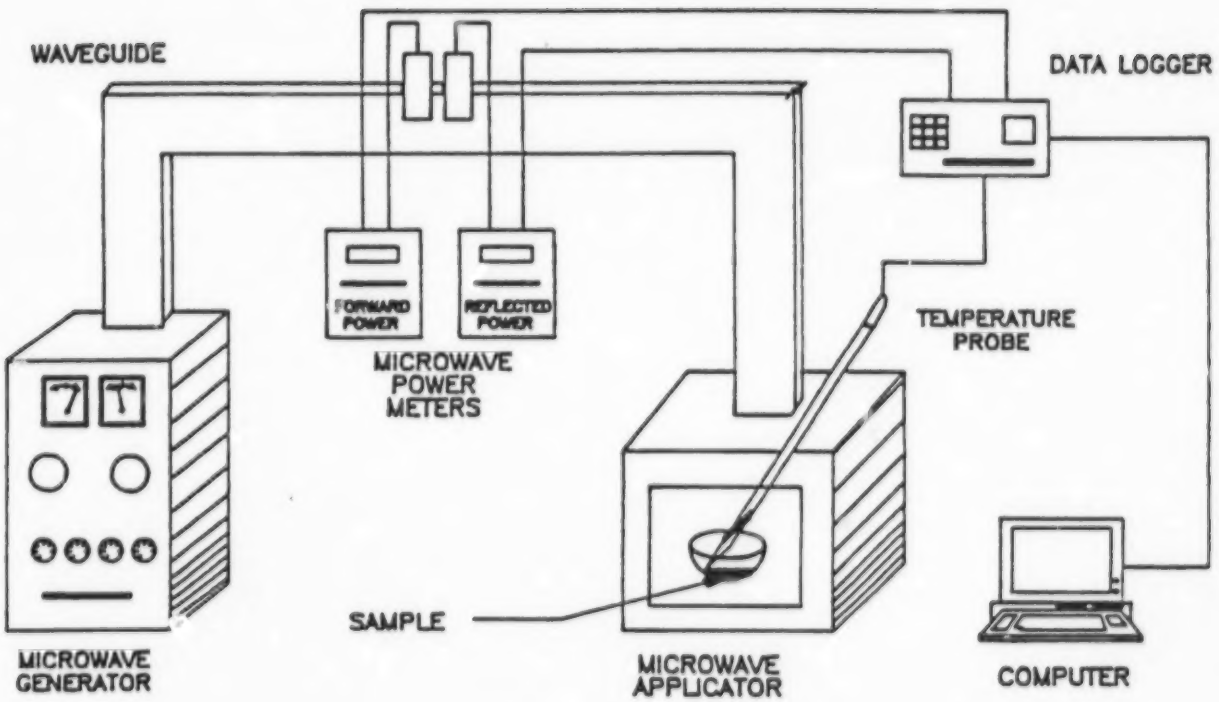

Figure 2. SCHEMATIC OF EXPERIMENTAL ARRANGEMENT

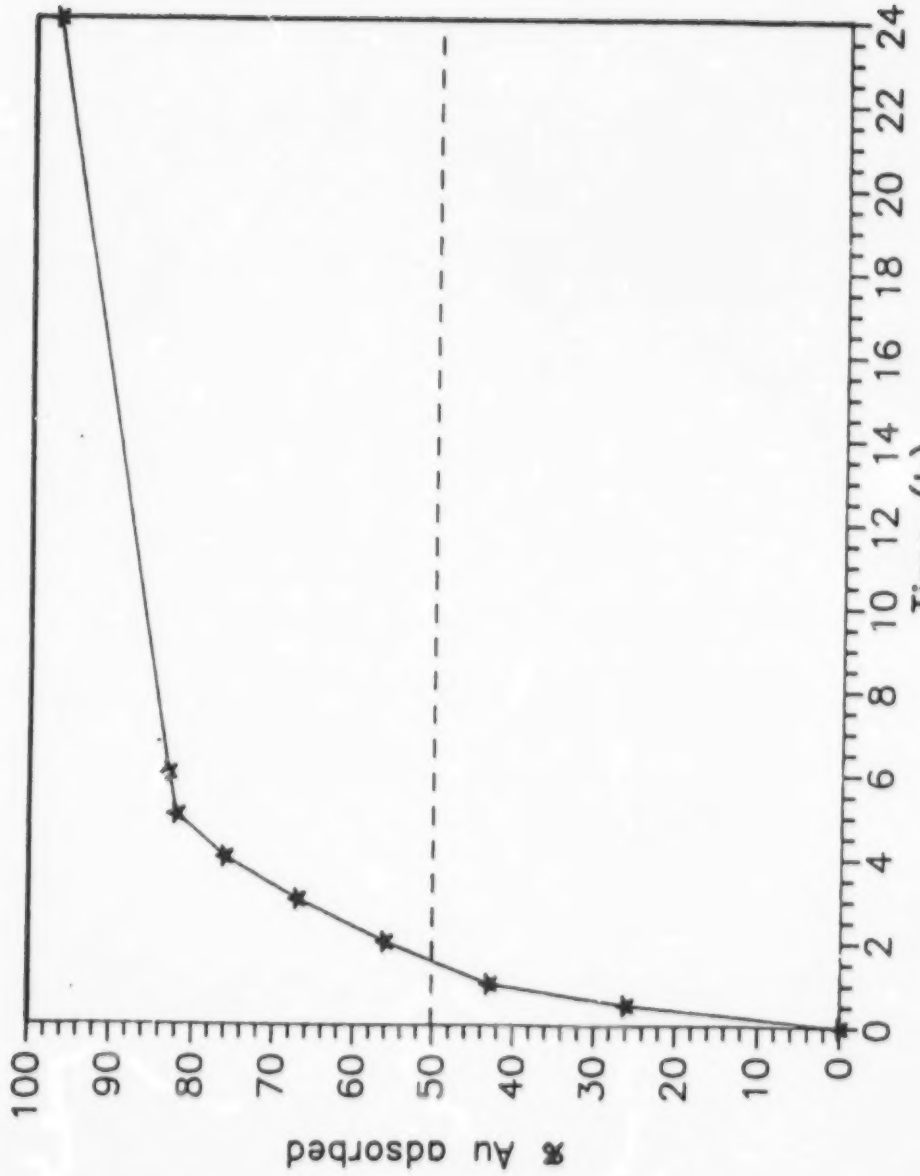

Figure 3. PLOT PERCENT OF GOLD ADSORPTION AGAINST TIME
(WET SPENT CARBON, 700°C, 2450 MHz)

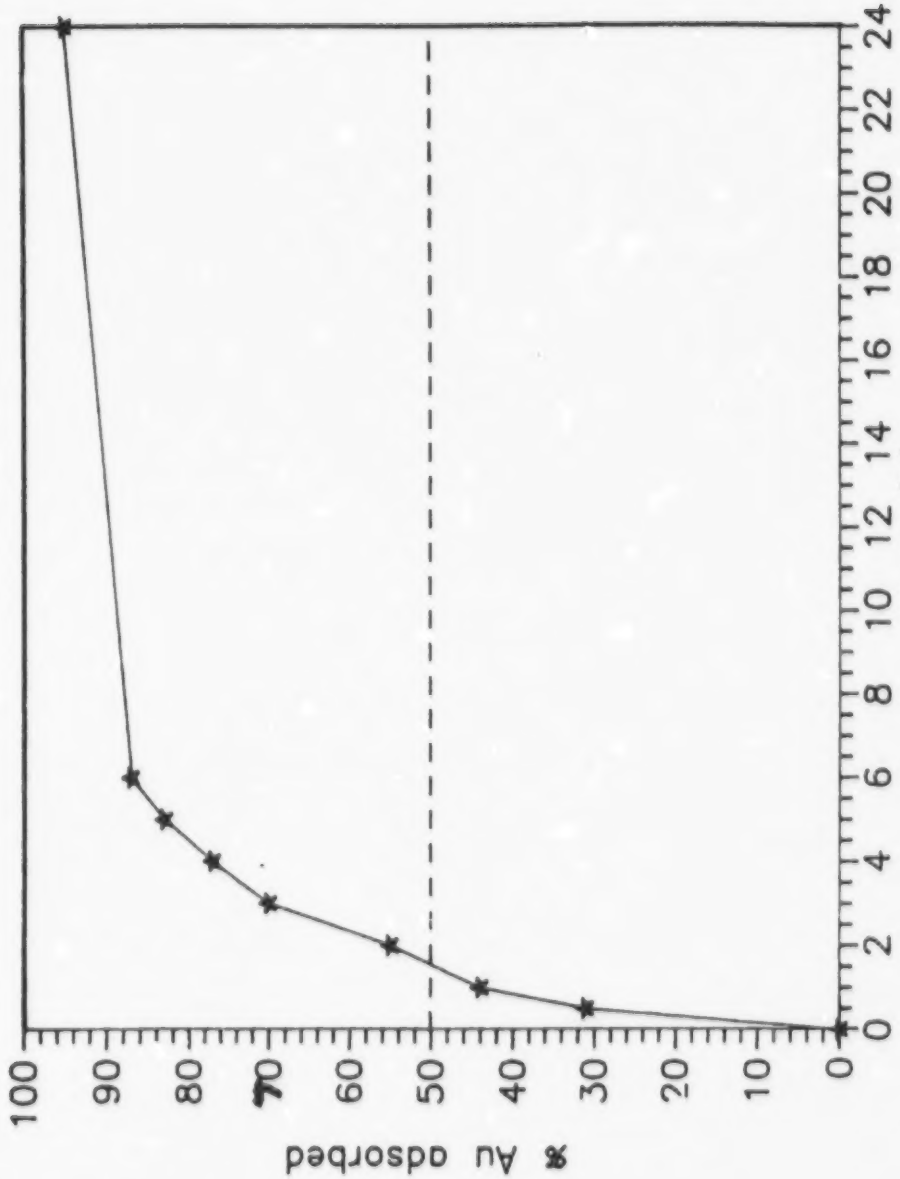

Figure 4. PLOT OF PERCENT OF GOLD ADSORPTION AGAINST TIME (WET SPENT CARBON, 750°C, 2450 MHz)

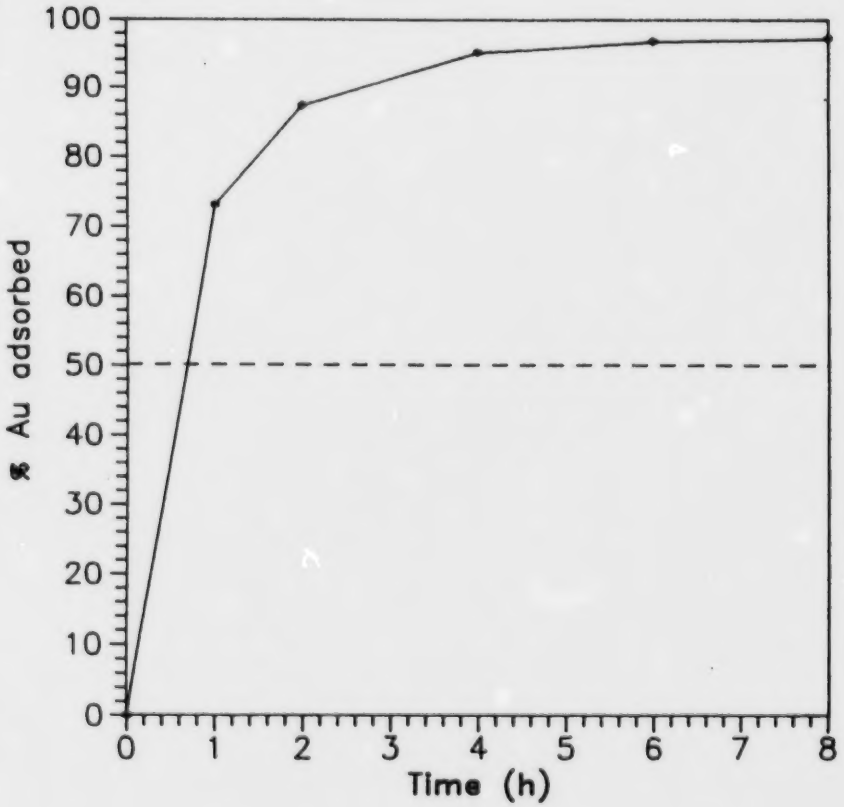

Figure 5. PLOT OF PERCENT OF GOLD ADSORPTION AGAINST TIME (WET SPENT CARBON, 700°C, 915 MHz)

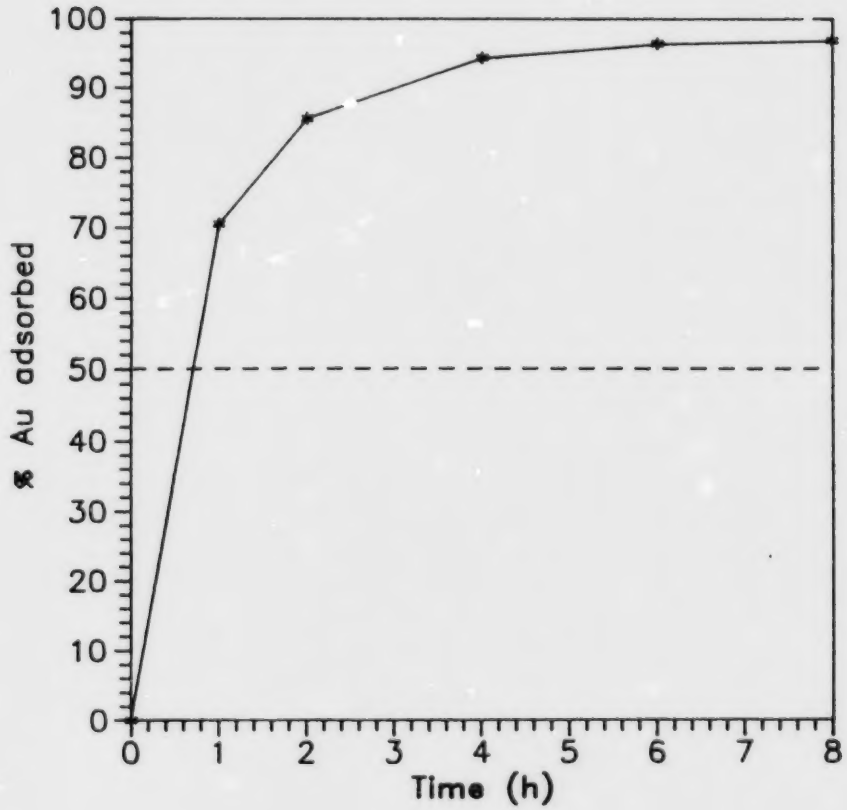

Figure 6. PLOT OF PERCENT OF GOLD ADSORPTION AGAINST TIME (WET SPENT CARBON, 750°C, 915 MHz)

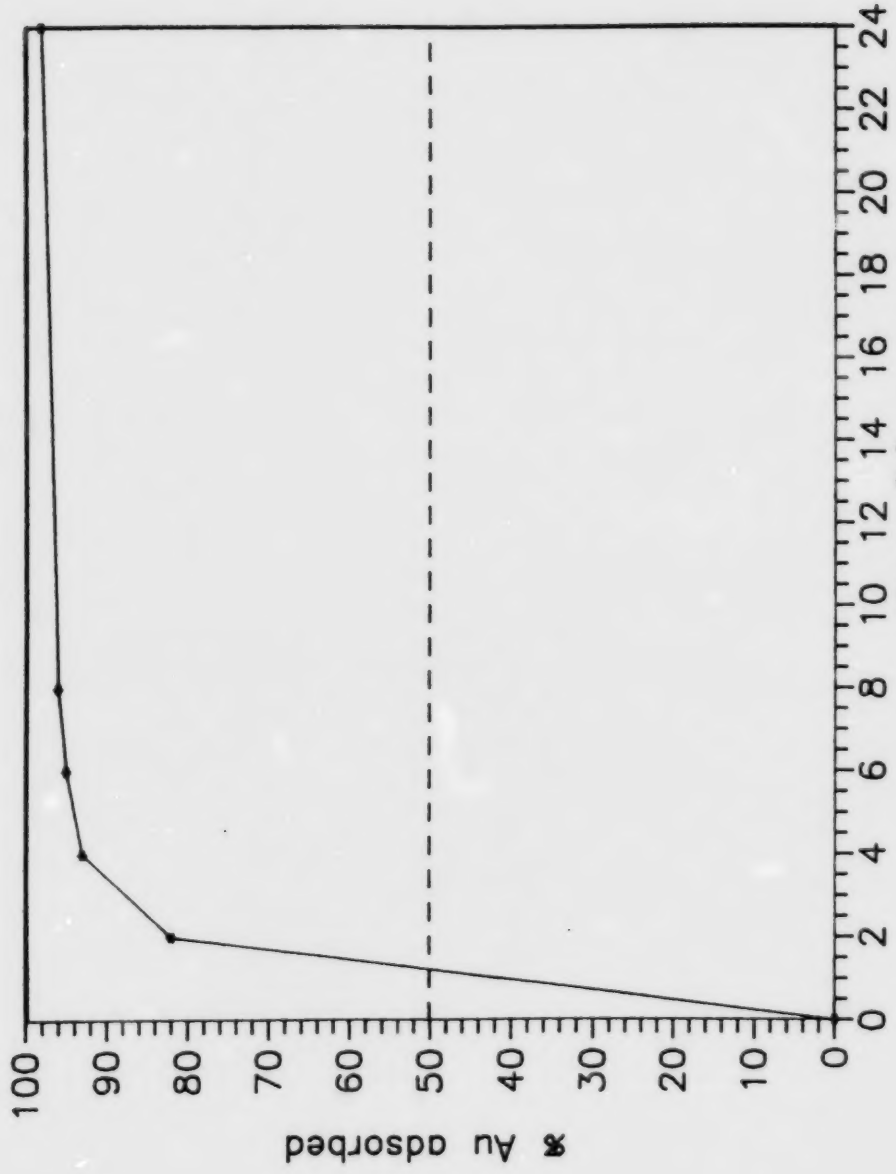

Figure 7. PLOT OF PERCENT OF GOLD ADSORPTION AGAINST TIME (DRY SPENT CARBON, 5 MIN., 2450 MHz)

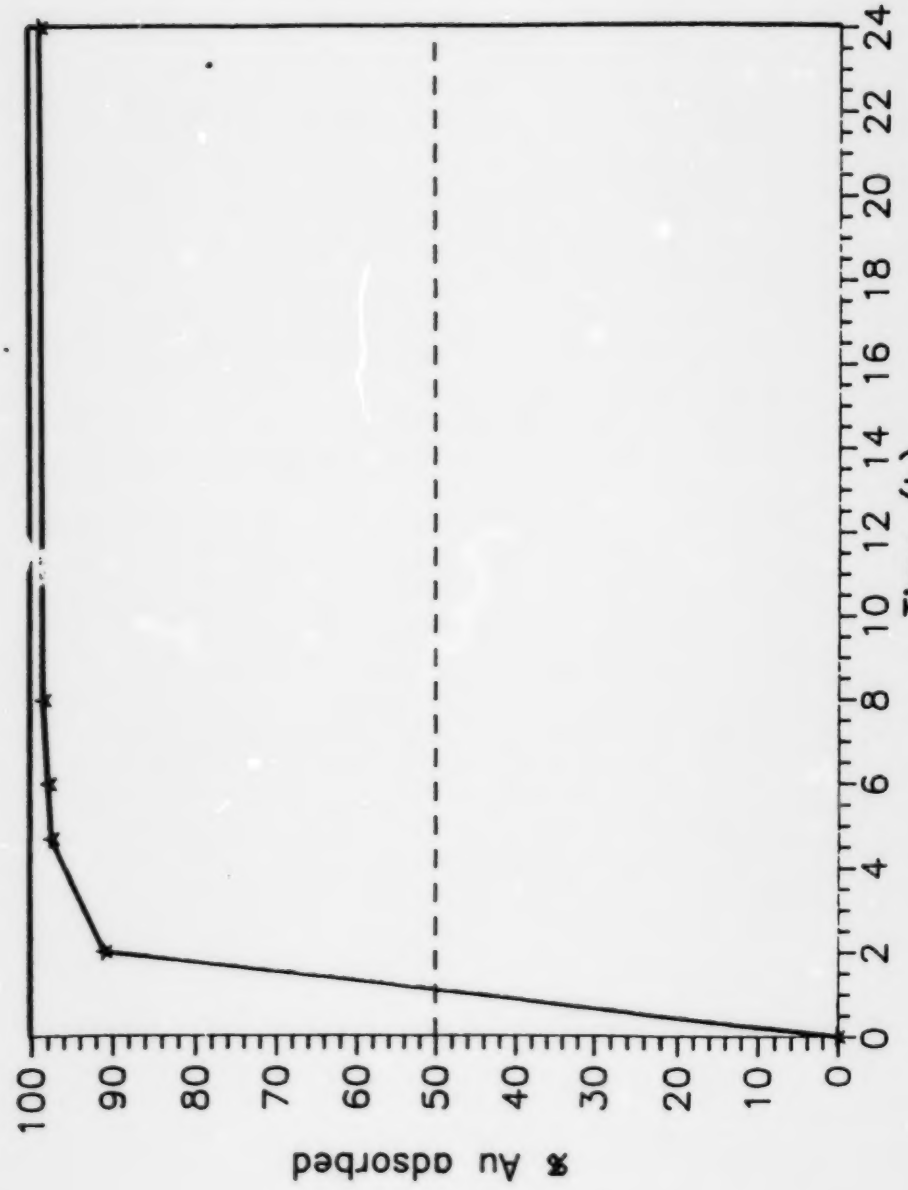

Figure 8. PLOT OF PERCENT OF GOLD ADSORPTION AGAINST TIME (WET SPENT CARBON, 5 MIN., 2450 MHz)

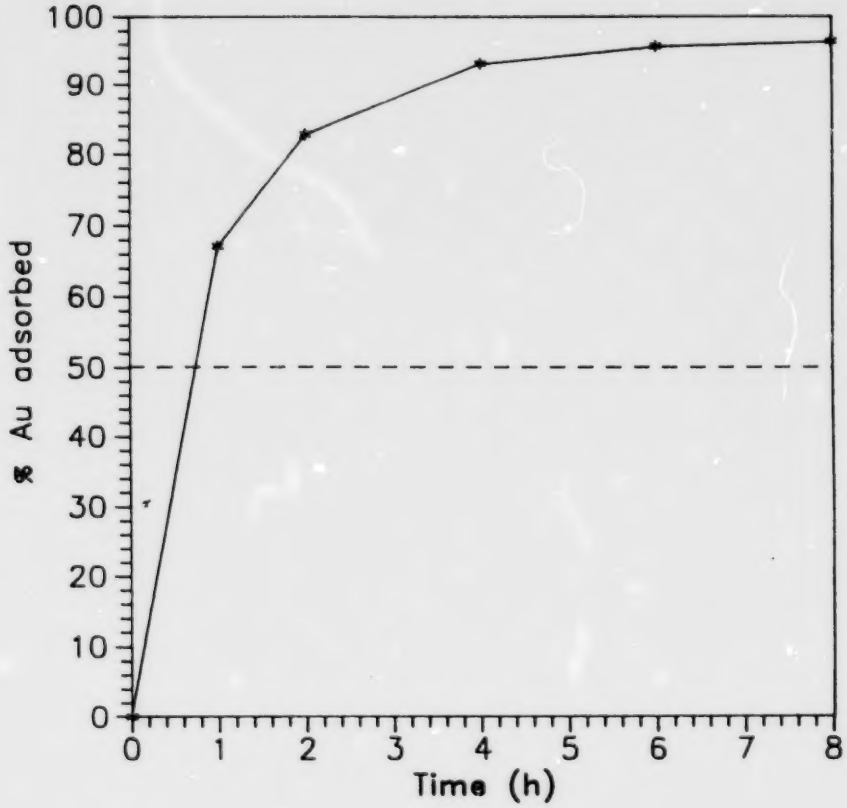

Figure 9. PLOT OF PERCENT OF GOLD ADSORPTION AGAINST TIME (DRY SPENT CARBON, 5 MIN., MHz)

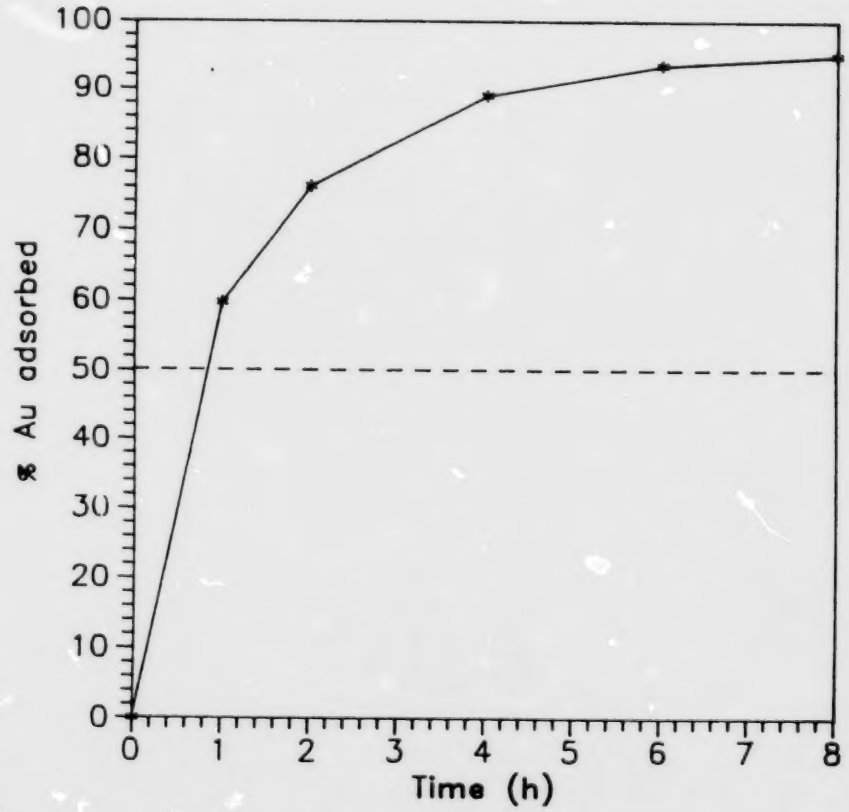

Figure 10. PLOT PERCENT OF GOLD ADSORPTION AGAINST TIME (WET SPENT CARBON, 5 MIN., 915 MHz)